A tectonically-induced Eocene sedimentary mélange in the West Ligurian Alps, Italy

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A TECTONICALLY-INDUCED EOCENE SEDIMENTARY MÉLANGE IN THE WEST LIGURIAN ALPS, ITALY

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ABSTRACT

The southern Alpine Foreland basin succession (Late Eocene – Early Oligocene?) lies over the Mesozoic condensed carbonate succession of the Provençal Dauphinois Domain, ends with a chaotic complex, and is overthrust by more internal Alpine units (San Remo-Monte Saccarello Ligurian unit) emplaced in Late Oligocene – Early Miocene times. The chaotic complex consists of debris flow paraconglomerates, breccias, and megablocks, up to km-sized. Despite the post-Eocene Alpine tectonics overprint, particularly intense in its uppermost part, the sedimentary origin of the chaotic complex is proved by the interbedding of paraconglomerates and breccias with fine-grained turbidites. Megablocks consist both of formations buried below the chaotic deposits (Mesozoic Provençal Dauphinois succession, Eocene Alpine Foreland basin succession) both of exotic units (Ligurian *Helminthoides* Flysch). Paraconglomerate and breccia clasts were sourced by the penecontemporaneous turbidite sands and muds as well as the same lithologies as megablocks. All these features suggest the activity of early Alpine Eocene strike-slip or transtensive fault systems that juxtaposed and exhumed the *Helminthoides* Flysch unit and the Provençal Dauphinois succession. Submarine ridges were generated and favoured rock fall phenomena that involved both small, mm- to dm-sized, clasts and huge slabs detached from the main rock masses. These morphostructural highs were flanked by oversteepened slopes affected by failures that gave rise to debris flows, involving hemipelagic muds and turbidite sands and lithified fragments of older formations, which resulted in strongly polygenic paraconglomerates. The studied mélange is thus

fully due to sedimentary processes that were, however, completely controlled by early Alpine tectonics.

1. Introduction

Mélanges, or chaotic deposits, crop out in a large part of the Western Alps at the top of the Alpine foreland basin succession. They are located immediately below a first order thrust surface overlain by internal Alpine units. These chaotic deposits consist of a variety of blocks, up to km-sized, of different lithologies and ages, floating in a muddy-sandy matrix commonly showing a pervasive slaty cleavage (e.g. Kerckhove, 1969; Homewood and Caron, 1982; Jeanbourquin et al., 1992). They are affected by different degrees of deformation, usually intense enough to make uneasy the understanding of the generative processes. These chaotic deposits were named in different ways, depending on the geographic and tectonic domain and on the interpretive model. One model calls upon a mechanism of shearing along tectonic thrust zones during offscraping (Burkhard, 1988; Jeanbourquin, 1994); another model envisions soft sediment deformation during mass gravity flows along tectonically active slopes developed at the front of orogenic wedges (Kaufmann, 1886; Lanteaume, 1968, 1990; Kerckhove, 1969; Debelmas and Kerckhove, 1973; Trümpy, 2006).

In the last years, a lot of work has been done on chaotic deposits and the attention of the authors has been focused on the individuation of the criteria useful to distinguish the different types of mélanges (Orange, 1990; Orange and Underwood, 1995; Pini, 1999; Cowan and Pini, 2001; Camerlenghi and Pini, 2009; Festa et al., 2010a, b). Their origin is commonly attributed to one, or a combination, of the following processes:

- tectonic disruption and mixing of originally coherent sequences that produce tectonic mélanges (Sengör, 2003), broken formations (Hsü, 1968; Pini, 1999) or tectonosomes (Pini, 1999; Camerlenghi and Pini, 2009);
- gravitational submarine downslope movements that produce sedimentary mélanges or olistostromes (Beneo, 1956; Flores, 1956; Abbate et al., 1970; Lash, 1987, Pini, 1999; Camerlenghi and Pini, 2009);
- shale diapirism caused by the uprise toward the sea floor of overpressured, fluid-permeated fine-grained sediments (Lash, 1987; Barber et al., 1986).

However, the role played by each process is difficult to state, because of the facies convergence of the products. Moreover, especially in collisional chains, deformation and metamorphism can often obliterate or hide the original relationships between the different elements that compose the chaotic deposits.

In this paper we present a detailed study of the chaotic deposits cropping out in the Western Ligurian Alps, along the Italian-French border (Fig. 1). A multidisciplinary approach, involving geological mapping, stratigraphy, petrography, and structural analysis, allowed to recognize that the primary features of the chaotic deposits are well preserved, and to correctly evaluate the effects of Alpine deformation. The main results of this study are the identification of the processes responsible for the chaotic deposit formation and a new hypothesis concerning the tectono-sedimentary evolution of this portion of the Alpine Foreland basin.

2. Geological setting

The study area is located in the Western Ligurian Alps, in the Argentina Valley, close to the Triora village. The Western Ligurian Alps are a stack of four main groups of tectonic units, which have always been assumed to correspond to four Mesozoic adjacent main paleogeographical domains: the Dauphinois and Ligurian Briançonnais domains as parts of the European continent; the Pre-Piedmont domain as the margin of the European continent; the Piedmont-Ligurian domain as the contiguous oceanic basin (Vanossi et al., 1984, 1991; Lemoine et al., 1986; Seno et al., 2005). (Fig. 1).

The Ligurian Briançonnais and Dauphinois domains consist of an Hercynian basement overlain by mainly Mesozoic carbonate successions developed during the evolution of the European Alpine Tethys passive margin. A regional discontinuity surface truncates the top of these successions and is overlain by the Eocene Foreland basin succession. These domains are deformed as a single one by Alpine tectonics to form a foreland fold and thrust belt detached over Triassic quartzites and evaporites. The metamorphic grade spans from very low in the internal sectors (Internal Ligurian Briançonnais) to anchimetamorphic or not metamorphic in the external ones (External Ligurian Briançonnais and Dauphinois) (Seno et al., 2005; Piana et al., 2009).

The study area is located within the southernmost part of the Dauphinois domain, known as Provençal Dauphinois Domain (Faure-Muret, 1955), that shows a Jurassic to Lower Cretaceous succession characterized by important gaps, reduced stratigraphic thicknesses, and much shallower facies with respect to the main part of the Dauphinois domain. The only term of the Mesozoic succession cropping out in the study area is represented by Upper Cretaceous marly limestones that document the drowning of the Provençal shelf into a hemipelagic environment.

The top of the Cretaceous sediments is truncated by an important unconformity, testified by an erosional surface with paleosoils, root traces and *Microcodium*, that indicates a prolonged emersion, spanning more than 20 my (Maastrichtian – Lutetian). The overlying Eocene succession has been interpreted as the result of the early stages of subsidence of the Alpine Foreland basin (Allen et al., 1991; Sinclair, 1997). This succession is subdivided into four lithostratigraphic units (Fig. 2):

- Trucco Formation (Lutetian ? – Lower Bartonian), discontinuous continental and estuarine-lagoonal sediments representing incised valley fills (Varrone and Clari, 2003; Varrone, 2004);
- Nummulitic Limestone (Bartonian), allochem sandstones deposited in a mixed siliciclastic-carbonate ramp or ramp limestones rich in calcareous red algae and encrusting foraminifera (Boussac, 1911, 1912; Varrone, 2004; Varrone and d'Atri, 2007). It is bounded at the base by a discontinuity surface related to a transgression due to the increase of tectonic subsidence rates (Varrone, 2004); where the Trucco Formation is absent, Nummulitic Limestone directly overlies the Upper Cretaceous marly limestones;
- *Globigerina* Marl (Upper Bartonian-Lower Priabonian), hemipelagic sediments rich in planktonic foraminifera that correspond to the drowning of the Nummulitic Limestone ramp (Varrone et al., 2002);
- Ventimiglia Flysch (Priabonian- Lower Oligocene?), turbidite deposits consisting of alternances of shales and fine to medium quartz- and mica-rich sandstones, with a sand-to-mud ratio markedly less than 1. It represents the lateral equivalent of the well known Grès d'Annot formation (Stanley, 1961).

This succession is truncated at the top by the basal thrust of Ligurian Units known as San Remo-M.te Saccarello Unit (Sagri, 1980, 1984, Vanossi, 1991) (Fig. 2). This unit belongs to the well known Cretaceous to Paleocene *Helminthoides* Flysch nappe. The San Remo-M.te Saccarello (SRS) unit consists of basin plain varicoloured pelites followed by a thick turbidite succession, made up of thickly bedded coarse grained sandstones, interbedded with thin layers of dark shales, in the lower part, and finer grained sandstones and limestones in the upper part. The whole succession has been dated to the Barremian - Maastrichtian interval (Manavit and Prud'homme, 1990; Cobianchi et al., 1991).

At the top of the Ventimiglia Flysch, just below the tectonic contact with the SRS, chaotic deposits with block-in matrix fabric occur (Fig. 2) that have been studied by many authors, since the 60's (Lanteaume, 1962, 1968; 1990; Vanossi, 1991; Giammarino et al., 2009, 2010). The overprint of Alpine deformation is very intense close to the SRS basal thrust. This led to different interpretations about the tectonic vs. depositional origin of these deposits that consequently were named with different terms: *Zone des Lambeaux de charriage* (Lanteaume, 1962); *Complexe olistostromatique* (Lanteaume, 1968, 1990); *Zona dei Lembi Interposti* (Vanossi, 1991) and Tectonic Unit of Baiardo-Triora (Giammarino et al., 2009, 2010) . The tectonic interpretation of the mélange underpins the existence of a shear zone in the upper part of the Ventimiglia Flysch. Our data seriously question this fact and constrain the general interpretive model as discussed below.

3. Methods of study

Field work included geological mapping and stratigraphical analysis with particular attention to the nature and provenance of clasts, and the block/matrix relationships. A structural analysis has been carried out in order to evaluate the degree of the tectonic deformation overprint. Several tens of peels and thin sections have been prepared from selected speciments from an extensive sampling of blocks, chaotic beds and matrix. Petrographic studies were carried out by optical microscopy and cathodoluminescence analysis (CITL 8200 mk3 equipment, working conditions: about 17 kV and 400 μA). In some samples coming from chaotic deposits, the content of calcareous nannofossil has been investigated in order to date clasts. The study of calcareous nannofossils was performed on simple smear slides prepared on unprocessed material following standard techniques (Bown & Young, 1999), using optical microscopy at 1250 X.

4. The chaotic deposits of the Ventimiglia Flysch

Chaotic deposits are mainly represented by: 1) paraconglomerates; 2) breccias; 3) megablocks. Paraconglomerates and breccias are organized in beds ranging in thickness from a few decimetres to several metres, randomly interbedded with turbidite sandstone-shale alternances. Megablocks range from decametre to kilometre in size and become more abundant up-section. These chaotic deposits are present only in the upper part of the Ventimiglia Flysch that consequently can be separated in a lower rank lithostratigraphical unit named Triora Olistostrome Member (TOM). Its lower boundary is placed at the base of the lowermost paraconglomerate bed. No major discontinuity, either tectonic or stratigraphic, has been detected at the base of the TOM, differently from what stated by previous authors (Lanteaume, 1990; Giammarino et al., 2010).

TOM crops out over a wide area (about 40 Km^2) and shows thickness changes from a maximum of 600 m in the central sector to about 300 m in the southern sector (Fig. 3). The mesoscopic and microscospic features of each kind of TOM chaotic deposits are hereafter described.

4.1. Paraconglomerates

Paraconglomerates were recognized in the whole study area. They occur as dm- to m-thick beds without any internal organization (Fig. 4A). These beds are interlayered with turbidite fine-grained sandstones and shales comparable to the lower part of the Ventimiglia Flysch. Clasts show different sizes, ranging from centimetre to metre, different shapes, from rounded to subangular, and different lithologies (Figs. 4B, C).

Mesoscopic and microscopic analyses allow to distinguish three groups of clasts on the basis of lithology and provenance in relation to the encasing formation of the TOM (i.e. the Ventimiglia Flysch): intraformational, extraformational and exotic clasts.

- *Intraformational clasts* derive from unprecised beds of the Ventimiglia Flysch. They consist of fine-grained sandstones, rich in quartz and mica grains, and dark shales (Fig. 4D);

- *Extraformational clasts* derive from lithostratigraphic units of the underlying stratigraphic succession, that includes the Eocene Alpine foreland basin and the Mesozoic Provençal Dauphinois successions. More in particular, clasts of the following formations have been recognized:

  - Jurassic limestones, consisting of packstones with peloids and skeletal fragments (gastropods and ostracods);
  - Upper Cretaceous marly limestones, that consist of mudstones and wackestones with planktonic foraminifera (*Globotruncanita elevata, Globotruncana arca, Globotruncana lapparenti*, *Rotalipora* sp.) dating the Campanian-Maastrichtian (Fig. 4E);
  - Eocene Nummulitic Limestone, represented by two different lithologies: the first consists of light grey massive rudstones with benthic macroforaminifera (*Nummulites perforatus, N. striatus*, *Discocyclina*, *Operculina*), encrusting foraminifera (*Solenomeris)*, miliolids, bryozoan, gastropod, red algae, and echinoderm fragments; the second is characterized by whitish sandstones with quartz and feldspar grains, dark clay chips and rare fragments of nummulitids.

- *Exotic clasts* derive from lithostratigraphic units referable to other palaeogeographic domains (Sengör, 2003). They are represented by bluish grey to whitish massive limestones that belong to the *Helminthoides* Flysch (Figs. 4F, G). Calcareous nannofossil analyses allow to date these clasts to the Late Paleocene (Thanetian). The rich assemblages recovered are referable to the NP6-NP7 zones of the zonation scheme of Martini (1971) because of the presence of *Discoasteroides bramlettei*, *Discoaster mohleri*, *Ericsonia subpertusa*, *Fasciculithus tympaniformis*, *F. bobii*, *Heliolithus cantabriae, Prinsius bisulcus*, *P. dimorphosus*, *Sphenolithus moriformis*, *Sphenolithus anarrhopus, Toweius eminens*, *T. pertusus*. Very few clasts made up of reddish, laminated, coarse siltite with quartz and mica occur and are comparable to the lowermost part of the *Helminthoides* Flysch.

Several ellipsoidal, dm-large concretions locally occur (Fig. 5). They consist of cemented portions of interbedded mudrocks and fine-grained sandstone layers locally showing parallel and convolute laminations. Sandstones contain sub-rounded to angular quartz grains, mica flakes, dolomite crystals, carbonate micropeloids and pyrite. Locally small and poorly preserved planktonic foraminifera occur. Calcite-filled, mm-thick, septarian veins are also recognizable. The marked textural contrast between the concretion and the surrounding paraconglomerate demonstrate that the concretions did not develop after paraconglomerate deposition but grew within mud-sand alternations and were subsequently reworked and included in the paraconglomerates. Lithological and sedimentological features suggest a Ventimiglia Flysch provenance for these concretions.

The clasts of paraconglomerates are disposed randomly into a muddy matrix that commonly contains submm- to mm-sized lithic grains, with the same composition of larger clasts (Fig. 4H). The fossil content of the matrix is quite scarce: microscopic analyses evidenced scattered reworked Middle Eocene planktonic foraminifera. Locally, the matrix of paraconglomerates consists of whitish medium- to coarse-grained sandstones with quartz and feldspar grains, dark shale clasts and fragments of macroforaminifera (*Nummulites*, *Discocyclina* and *Operculina*). These sediments point to a reworking of unlithified Eocene sediments.

Cathodoluminescence observations allow to distinguish and correlate cementation stages in matrix and clasts. In the matrix many monocrystalline sparry calcite grains occur. They are subangular and commonly some 10’s μm large (Figs. 6A, B). CL analyses show that they are characterized by a dull core overgrown sintaxially by an orange luminescing rim. The same luminescence characterizes a finer grained calcite that makes up the pelitic matrix cement. CL also enables to further distinguish within pelite and siltite clasts on the basis of their colour (Figs. 6C, D). Some clasts show the same moderate orange luminescence as the matrix whereas others are very dully luminescing. Because the luminescence of these terrigenous sediments, mainly composed of non-luminescent grains (quartz, micas, clay) is due to the luminescence of the intergranular carbonate cement, it may be concluded that some sediments were fully lithified before being reworked as clasts in the paraconglomerates, whereas others were still porous and were cemented subsequently, together with the matrix.

Paraconglomerates are commonly crossed by veins. Two main systems of veins may be recognized. The first system consists of veins up to 2-5 cm wide, filled with non luminescent sparry calcite and minor non luminescent quartz. These veins, that cross cutting relationships show to be the youngest, may be followed for several metres across the outcrop and are interpreted as tectonic veins related to post-Eocene deformation events. The second system is composed of much smaller veins, usually some tens of μm thick (Figs. 7A, B). They are locally closely spaced and give rise to dense swarms which are mainly perpendicular to bedding. Veins are mainly filled with orange luminescent sparry calcite. These veins show a very irregular shape: they are discontinuous on a scale of a few centimetres, and appear crumpled and broken. Commonly these veins do not cross through clasts but are restricted to the matrix and follow the clast-matrix contact (Fig. 7C). Veins, with the same features as those occurring in the matrix, may occur within, or at the border of, clasts and end at the clast edge (Figs. 7E, F). Locally, vein swarms are confined within subvertical, dm-large “channels” that are bounded from adjacent undisturbed sediments by a sharp, irregular surface (Fig. 7D). Dm-sized slabs of the enclosing turbidite sandstone beds may occur within the veined pelitic portion and are grossly aligned with the prevailing vein direction.

4.2 Breccias

Breccia deposits occur only in the northern sector of the study area (Rocca Barbona), in the upper part of the TOM. They make up a 20 m thick interval and are interbedded with the turbidite succession (Figs. 8A, B). Breccias are organized in beds that range in thickness from 10 cm to several metres, with basal erosional surfaces (Fig. 8C). Both matrix- and clast-supported textures have been observed (Figs. 8A, D, E). The clasts are angular to sub-angular; in thin beds their size range from mm to cm, whereas over 70 cm large clasts occur in the thickest beds. Clasts are made up of lithologies referable to Triassic and Jurassic terms of the Provençal Dauphinois succession such as yellowish to whitish dolostones, dolomitic breccias, quartz-arenites, or oolitic limestones (Fig. 8E). The matrix has a calcareous composition and contains scattered nummulitid fragments (Fig. 8F). In matrix-free beds, clasts are compenetrated along pressure dissolution contacts (Fig. 8D). Clasts, also of large size, locally occur scattered within the interbedded turbidite pelite intervals (Fig. 8B).

4.3. Megablocks

The most striking feature of the TOM is the presence of huge blocks, hm to km large, embedded in a matrix consisting of paraconglomerates or pelites, and concentrated in the upper part (Fig. 3). Megablocks are subdivided into two big families: extraformational and exotic blocks.

Some extraformational blocks consist of only one lithostratigraphic term: Upper Cretaceous marly limestones rich in planktonic foraminifera (*Globotruncanita elevata* and *Globotruncana arca*), or Nummulitic Limestone, consisting of rudstones with macroforaminifera (*Nummulites perforatus, N. striatus*, *Discocyclina*, *Sphaerogypsina, Actinocyclina* and *Rotalia*), miliolids, echinoderm debris and red algae. In other cases, instead, the megablocks consist of more or less complete portions of a Mesozoic-Cenozoic succession: Upper Cretaceous grey marly limestones overlain, with an erosional surface, by m-thick beds of bioclastic rudstones (Nummulitic Limestone) close to Corte village (Figs. 3, 9A); a condensed succession ranging from Triassic dolostones to Eocene turbidites at Rocca Barbona (Fig. 9B).

The exotic megablocks reach the largest size, up to km-large, and are made up of huge slabs of the *Helminthoides* Flysch succession. The two best examples crop out respectively close to the Triora village, and at Colla Langan (Fig. 3). The first is made up of m-thick bluish grey massive limestone beds with *Helminthoides* trails interbedded with thin layers of dark shales. The second block is better exposed and consists of interbedded dm- to cm-thick laminated arenites and cm-thick dark shales passing to alternations of m-thick layers of bluish grey limestones and dark dm-thick shales. Nannofossil analyses document a Late Cretaceous age (post Santonian) on the basis of the occurrence of *Calculites obscurus*, in assemblage with *Lucianorhabdus* sp., *Micula staurophora*, *M. swastica*, *Watznaueria* sp. The lowermost part of the block shows a chaotic structure characterized by disharmonic folds and bed disruption (Fig. 9C). Just below the block, paraconglomerates are present.

5. Structural setting of the Ventimiglia Flysch in the study area

The Ventimiglia Flysch of the Triora - M. Saccarello area is presently comprised in the West Ligurian fold and thrust belt, where it is placed between the Eocene Foreland basin succession, resting on Provençal-Dauphinois folded units, and the Ligurian SRS unit overthrust at the top of the geometric sequence (Fig. 3). In this framework, the Ventimiglia Flysch was intensively sheared just below the SRS basal thrust and deformed by flexural-slip, open to tight folds consistent with those of the underlying Provençal-Dauphinois units. The deformational processes related to this tectonic configuration induced the development of widespread and/or penetrative foliations, consisting in a cm-spaced dissolution cleavage in the more competent levels and a mm-spaced cleavage in the pelite levels (Fig. 10A).

These foliations fully overprint the beds or primary structures only in some places, as in the SRS basal thrust zone or close to some other minor contractional shear planes that locally occur in the footwall of the SRS thrust unit (Fig. 10B).

Despite this deformational setting, that originated in anchimetamorphic conditions (Battaglia et al., 2011), the sedimentary origin of the TOM can be still ascertained, as widely described below. The sedimentary bedding can be still largely recognized (although often re-activated as slip plane during the flexural folding), the tectonic spaced cleavage does not completely mask the depositional textures and rarely affect the paraconglomerate clasts or the megablocks, whose primary contacts with the matrix can be still observed (Figs. 10C, D)

6. Interpretation

6.1. Stratigraphy and sedimentology

TOM is a composite chaotic body, some hundred metres thick on the whole, consisting of m-thick beds of paraconglomerates alternated with turbidite sediments and including m- to km- large blocks. It is thus characterized by a block-in-matrix fabric recognizable at all scales, from mm-scale of the matrix of the paraconclomerates to km-scale of the megablocks.

Different lines of evidence, both sedimentologic and tectonic, lead to infer a sedimentary origin for the TOM:

- paraconglomerates and breccias are repeatedly interbedded with turbidites throughout the whole TOM succession. This fundamental feature has never been described before even in papers in which the sedimentary origin of the chaotic deposits was stated but not supported by undisputable data (Lanteaume, 1990; Vanossi, 1991);
- poligenicity and textural features of paraconglomerates: the occurrence of extraformational and exotic clasts, the complete lack of any internal organization, the great size variability of clasts, and their substantially equidimensional geometry are all elements characteristic of sedimentary mélange and are not found in broken formations (e.g. Pini, 1999; Camerlenghi and Pini, 2009);
- absence of a major tectonic contact at the base of the TOM.

As a consequence TOM is definitely interpreted as fully generated by sedimentary processes, i.e. it can be considered an example of olistostrome or sedimentary mélange. The upper part of the TOM is characterized by a greater degree of deformation: the matrix shows a pervasive slaty cleavage (mm- to cm-spaced), and the megablock-matrix boundaries display evidence of shear. The evidence provided above, however, clearly show that this part of the TOM mélange is not generated by tectonic processes but simply results from the overprint of subsequent Alpine deformation stage linked to the emplacement of the SRS unit.

Once ascertained the sedimentary origin of the TOM, a sedimentological interpretation is to be discussed. Four deposits are distinguished:

- fine to medium sandstone-shale alternances, with a sand-to-mud ratio markedly less than 1, indicate starved turbidite sedimentation in a protected part of the Grès d'Annot basin;
- paraconglomerates: the matrix support, the great size variability of the clasts, the absence of any internal organization clearly point to debris flow processes along submarine slopes;
- breccias: the prevailing clast support, ubiquitous in the thickest beds, and the angular shape of clasts, all constituted by Triassic and Jurassic carbonate rocks, suggest rock fall processes with a short transport distance affecting the toes of steep scarps developed within fully lithified rocks;

- megablocks: embedded within turbidites and/or paraconglomerates document catastrophic detachments of huge slabs from the same scarps that delivered the cm-to dm-sized clasts of breccias.

6.2. Early diagenesis

A conspicuous set of data indicates that, unexpectedly in deep sea siliciclastic sediments, carbonate precipitation took place in an early diagenetic stage, during deposition of the TOM:

- concretions, that do not show the block-in-matrix fabric, document that they are the result of early and selective cementation of portions of mudrocks and/or fine grained sandstones immediately preceding their involvement in the mass gravity flows as lithified masses;
- pelitic clasts showing a luminescence different from that of the paraconglomerate matrix evidence that some beds of the turbidite succession, similarly to concretions, experienced a cementation before failure;
- clasts crossed or bordered by veins that do not continue into the matrix demonstrates that opening and filling of veins occurred within unconsolidated sediments that could be involved in mass gravity flows, i.e. at a very shallow burial depth. The similarity of these veins with those that make up the dense swarms crossing the whole paraconglomerates provides a clue for referring also the latters to an early diagenetic stage. This is also confirmed by their irregular and anastomosed pattern and the fact that veins do not crosscut through clasts and matrix but follow the clast-matrix boundary. This suggests a partitioning of the flow of fluids, from which carbonate precipitated, within a rheologically heterogeneous medium consisting of scattered indurated clasts and a prevailing loose pelitic matrix. The crumpled and broken aspect, at last, may be referred to slight remobilization of the debris flow plastic deposits and/or to burial compaction (Fig. 11).
- sparry calcite grains, widespread in the paraconglomerate matrix, are absent in turbidite sandstone beds. By converse, quartz and mica grains, that are the main component of sandstones, do not occur in the paraconglomerate matrix. This indicates that the calcite grains are not detrital but authigenic. Moreover, all calcite grains are distinctly concentrically zoned with a dull luminescing core and a grossly isopachous rim showing the same orange luminescence of veins. This points to a growth of calcite within the matrix. However, the occurrence of scattered calcite grains, up to 150 µm in size, shows that calcite precipitation was not diffuse to all the sediment porosity but concentrated in discrete spots. The dull cores therefore represent pre-existing fragments acting as preferential sites for a sintaxial precipitation of calcite rims (Fig. 11). The latters grew displacively and isopachously, i.e. in all directions,

within loose, very porous, clayey sediments in the same time as orange luminescing veins. The dull luminescing cores could correspond to fragments of first stage veins opened within debris flow deposits that were subsequently affected by ongoing mass gravity movements.

7. Discussion

Any interpretive model of the TOM must give an explanation to the following aspects:

1) what triggered debris flows?

2) what triggered megablocks emplacement?

3) why debris flows show a great lithological variability of clasts?

1) Failure mechanisms along submarine slopes, giving rise to mass gravity flows, are related to the fact that shear stress on sediment packages exceeds their shear strength. This in turn may be due either to an increase of shear stress and/or a reduction of sediment shear strength (e.g. Spence and Tucker, 1997). Slope oversteepening, due to tectonic tilting or to erosion at the toe of slope, and the impact of high energy events, such as storms and tsunamis on the sea floor, are the most cited examples of processes increasing shear stress on submarine sediments. Storms and tsunamis may be ruled out in a turbidite basin whereas erosion of the slope cannot be verified in the study area. A sudden increase in pore water pressure is considered to be the major dynamic control on sediments shear strength. Large amounts of fluids may be rapidly delivered, and cause overpressure in sediment pores, by processes like gas hydrate dissociation (e.g. Haq, 1993; Paull et al., 1996; Henriet and Meniert, 1998), diagenetic conversion of biogenic silica into opal CT (Davies et al., 2006; Davies and Clark, 2006), and seismic shocks. No silica-rich sediments are present in the whole Meso-Cenozoic stratigraphic succession of the study area, and no positive evidence of massive methane flux through the sediment column, such as the occurrence of large masses of CH_4-derived carbonates (e.g. Campbell, 2006; Clari et al., 2009), are recognizable. Oversteepened slopes and seismic shaking, in turn inducing fluid overpressures, appear hence as the most probable processes triggering these debris flow phenomena.

2) The most impressive feature of the TOM is the occurrence of huge blocks mainly concentrated in the upper part. Megablocks of comparable or even greater size are well known in several examples of giant submarine landslides on present continental margins such as the Storegga slide on the Norwegian margin (Bugge et al.,1988), the Hinlopen slide in the Arctic Ocean (Vanneste et al., 2006), and the Saharan Debris Flow on the Angola offshore (Masson et al., 1993; Gee et al., 1999, 2006). Inferred failure mechanisms for these examples include gas

hydrate dissociation and resulting fluidification of overlying sediments; seismicity related to glacio-isostatic processes acting on contouritic clays in which overpressures developed as a consequence of rapidly deposited massive glacigenic debris flows; tectonic activity resulting in fault-block tilting and slope oversteepening, seismic shocks, and an effective fluid flow focussed within fault-related conduits. All these slides, however, involve sediments deposited on continental slopes, i.e. strictly intrabasinal deposits. They include both loose sediments and more consolidated layers that give rise to slabs up to km-size. In the TOM, by converse, the majority of megablocks are exotic (*Helminthoides* Flysch), i.e. they are not constituted by portions of the underlying stratigraphic succession but pertain to other structural and paleogeographic units. The geological context, therefore, is more complex than those of the giant slides cited and necessarily implies Eocene tectonic events that coupled and juxtaposed the *Helminthoides* Flysch unit to the Provençal Dauphinois succession. In such a setting, tectonics played a major role also in generating catastrophic collapses of huge slides detached from highly fractured, fault-bounded rock masses, exposed at the sea floor and subject also to seismic shocks.

3) Similarly to megablocks, also paraconglomerates are markedly polygenic since they include intraformational clasts, extraformational clasts coming from the lithostratigraphic units underlying the Ventimiglia Flysch (from Jurassic to the Eocene Nummulitic Limestone) and exotic ones (*Helminthoides* Flysch Ligurian Unit). This lithological feature makes the paraconglomerates of the TOM rather peculiar as they texturally fit the classical model of intrabasinal debris flows and are organized in usually m-thick beds, but the occurrence of extraformational and exotic clasts makes them a sort of miniature olistostromes. Paraconglomerates of the TOM, in other words, cannot result from simple failures of slopes on which hemipelagites and thin turbidites were being deposited, but imply the same geotectonic setting envisaged above for the megablocks. The absence of any organization and the random distribution of clast lithologies within paraconglomerate beds indicate failure of portions of stratigraphic successions in which compositionally different beds (lithoclastic breccias, sourced by older rock masses, and loose turbidites, locally bearing concretions or selectively cemented beds) were alternated. During the downslope flow, beds were almost completely disrupted and clasts randomly mixed in a fluidized pelitic matrix.

In summary, on the basis of described data and interpretation the following scenario may be defined:

- During the Late Eocene – Early Oligocene (?), turbidite deposition in the Ligurian sector of the Alpine Foreland basin was affected by a sudden inception of mass gravity flows. Steep faults activated and juxtaposed successions of different tectonic units and exhumed older rocks (Triassic to Eocene in age) pertaining to different domains (Provençal Dauphinois Domain, Alpine foreland basin and *Helminthoides* Flysch unit) (Fig. 12). The morphological expression of these fault systems was represented by submarine ridges. These structures were likely heralded, during deposition of the lower part of the Ventimiglia Flysch, by formation of intrabasinal sills, oriented transversally to the turbidite basin axis. They confined this area and limited the arrival of large amounts of sand, longitudinally fed from southern source areas (Stanley & Mutti, 1968), insofar determining the marked facies contrast of the Ventimiglia Flysch sand-poor turbidites in the study area compared to surrounding areas.
- Fault-bounded ridges were affected by rock fall gravitational movements that involved both small, mm- to dm-sized, clasts and huge slabs (megablocks) detached from the main rock masses (Fig. 13). This debris accumulated at the feet of the cliffs and likely spread distally as thin sheets along more gentle depositional slopes where turbidites were being deposited. Along these slopes other gravitational processes, such as debris flows, involved lithified fragments of older formations and turbidite muds and sands, mainly loose but also containing portions with a higher degree of coherence (concretions, partly cemented beds), giving rise to strongly polygenic paraconglomerates. Megablocks could also be involved in these polyphase gravitational movements together with paraconglomerates.
- In the mean time, carbonate-saturated diagenetic fluids flowed upward along steep faults through the Ventimiglia Flysch inducing localized calcite precipitation as concretions, selected beds, and swarms of veins. The alternation of mass gravity flows and cementation documents the concomitance of the two processes and suggests a role of fluids in triggering slope failures.

The above described scenario depicts a geological framework more consistent with deposition of TOM in an articulated fault-bounded basin, bordered by steep and deep-rooted faults, than an accretionary complex frontal trench dominated by the propagation of thrust systems, as suggested by Vanossi (1991) *(Zona dei lembi interposti* or *Complesso di progressione)*. Clasts and megabocks therefore were sourced by *Helminthoides* Flysch units, proximal to the paleo-European margin, that by Late Eocene – Early Oligocene (?) time had been tectonically juxtaposed with the Provençal Dauphinois succession during a very early Alpine, likely strike-slip or transtensive, tectonics, prior to the onset of the Ligurian fold and thrust belt. Actually, a strike slip fault activity is documented in adjoining sectors to start before and continue after TOM deposition. Stratigraphic data point to the generation of Early Cretaceous fault-related paleoescarpments (Bertok, 2007), whereas structural analysis show the existence of an important transpressive shear zone (Limone Viozene Deformation Zone: Piana et al., 2009) which, from the Oligocene onwards, played an important role in an East-West wide transfer (Stura couloir: Ricou, 1981; Lefevre, 1983) that allowed an independent kinematics of Ligurian Alps with respect to the Western Alps (Molli et al., 2010).

Our interpretation is also supported by the fact that a purely contractional tectonic regime in West Ligurian Alps started only some million years after the end of TOM deposition, maybe in the Late Oligocene-Early Miocene, as firstly suggested by Ford et al. (1999) on the basis of tectonic load modeling. This is also indicated by the occurrence of the oldest pervasive tectonic foliation (Fig. 14) of Ligurian Alps in all the terms of the foreland basin lithostratigraphic succession (see also Piana et al., 2009). Furthermore, the only thrust clearly recognizable in the West Ligurian Alps is the one presently placed at the base of the SRS Unit. This shear zone still preserves a regular flat geometry that laterally extendes for several tens kilometers and clearly displaces two orders of pervasive tectonic foliations recognized in the West Ligurian Alps. This points to a late (Early – Middle Miocene?) final emplacement of the SRS unit, related to the third main tectonic event recognized at regional scale in the Ligurian Alps. The SRS unit was therefore already interpreted as a shallow crustal thrust sheet (Ford et al., 1999), as also confirmed by recent thermometric (illite crystallinity) data (Battaglia et al., 2011) indicating that the SRS Unit reached a maximum T of about 180°, with respect to more than 250° recorded by the geometrically lower Briançonnais and Dauphinois units. The proposed interpretation is also confirmed by the age difference between the SRS Unit, fully referable to the Late Cretaceous (Manavit and Prud'homme, 1990) and the *Helminthoides* Flysch clasts within the TOM, that are partially dated to the Paleocene.

In conclusion, the overall features displayed at present by the TOM are the final result of the complex interplay through time of several geological processes: syndepositional transcurrent faulting activity, fluid expulsion, mass wasting, and burial compaction. Substantially, TOM is a chaotic complex fully due to sedimentary processes but completely controlled by a very Early Alpine tectonics, and successively deformed and incorporated into the Ligurian Alps foreland fold and thrust belt.

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CAPTIONS

Fig. 1
Location of the study area (black square). Modified after Lanteaume (1968).

Fig. 2
Schematic log of the succession cropping out in the study area (not to scale).

Fig. 3
Geological map of the Triora area, high Argentina valley.

Fig. 4
Main features of paraconglomerates clasts and matrix
A) Paraconglomerates organized in m-thick beds without any internal structure. The lower part show few dm-sized blocks (white arrows) floating in a muddy matrix; the upper part is characterized by more abundant and smaller clasts (Colla Langan sector). Hammer for scale is 35 cm long.
B) Subangular dm-sized clast of Ventimiglia Flysch sandstones embedded in a muddy matrix in turn containing submm- to mm-sized lithic grains (see also fig. 4h) (Gavano sector). Hammer for scale is 35 cm long.
C) Polished slab showing rounded to subangular clasts of different composition and size (HF: *Helminthoides* Flysch; VFs: Ventimiglia Flysch sandstone; VFp: Ventimiglia Flysch pelite) (Gavano sector).
D) Photomicrograph showing mm-sized intraformational clasts of different Ventimiglia Flysch beds. VFs: Ventimiglia Flysch sandstone clast; VFp: Ventimiglia Flysch pelite (Colla Langan sector).
E) Photomicrograph showing a sub-cm-sized extraformational clast of the Upper Cretaceous marly limestone. Detail of a Cretaceous planktonic foraminifer in the blow-up square (Colle Ardente sector).
F) Rounded m-sized exotic clasts of *Helminthoides* Flysch scattered in a fine grained matrix (Colla Langan sector). Hammer for scale is 35 cm long.
G) Photomicrograph showing the co-occurrence of rounded to subangular, submm- to mm-sized, intraformational (VFs and VFp) and exotic (HF) clasts. HF: *Helminthoides* Flysch clast; VFs: Ventimiglia Flysch sandstone clast; VFp: Ventimiglia Flysch pelite (Gavano sector).
H) Muddy matrix of paraconglomerates characterized by submm- to mm-sized lithic grains, with the same composition of larger clasts (Gavano sector). Pencil for scale is 14 cm long.

Fig. 5
Dm-large concretion consisting of fine-grained muddy sandstone (Andagna sector).

Fig. 6
Cementation features of paraconglomerates (Andagna sector).
A, B) TL and CL photomicrographs showing subangular, 10’s μm large monocrystalline sparry calcite grains scattered in the matrix. Note in B the dull core overgrown sintaxially by a luminescing rim.
C, D) TL and CL photomicrographs showing mm-sized clasts of Ventimiglia Flysch with different composition and luminescence. Clast (1) is a pelite and shows the same luminescence as the matrix; clast (2) is a siltstone and shows a very dull luminescence.

Fig. 7

Main features of irregular calcite-filled veins crossing paraconglomerates (A, B, D, E: Andagna sector; C, F: Colleardente sector).
A) Polished slab showing a dense swarm of some tens of μm-thick veins. Note the irregular and discontinuous shape of the veins.
B) Photomicrograph of the veins highlighting their crumpled and broken aspect and their sparry calcite infilling.
C) Paraconglomerate sample showing that veins, developed within the matrix, do not cross the clast. Finger tip for scale.
D) Polished slab showing that veins are restricted into a subvertical “channel” bounded from the surrounding sediments by an irregular and sharp surface (white arrows).
E, F) TL and CL photomicrographs showing a vein occurring at the border of a Ventimiglia Flysch clast and ending at its edge. Note in F) that the vein has the same luminescence of the monocrystalline sparry calcite grain rims (Fig 6A, B).

Fig. 8
Main features of breccia deposits in the Rocca Barbona area.
A) dm-thick layer of breccia (Br) interbedded with sandstone-shales turbidite couplets. Hatched black lines point to the lower and upper breccia boundaries. Lens cap for scale is 6.5 cm in diameter.
B) Alternation of dm- to m- thick breccia beds (Br) and m-thick turbidite beds. Note the occurrence of a 70 cm-large clast (black arrow) scattered within shales.
C) Thick bed of clast-supported breccias interbedded within shale beds. Hammer for scale is 35 cm long (black circle).
D) Detail of clast-supported breccias characterized by angular to sub-angular cm-sized clasts made up of lithologies referable to different formations of the Provençal Dauphinois succession (Td: Triassic dolostone clast; Jl: Jurassic limestone clasts). Note that the clasts are compenetrated along stylolitic contacts.
E) Photomicrograph showing the different composition of breccia clasts: Td: Triassic dolostone clast, Jw: Jurassic bioclastic wackestone clast; Jgr: Jurassic grainstone.
F) Polished slab showing Triassic dolostone clasts (Td) and Jurassic limestone clasts (Jl) scattered in a calcareous matrix with sparse nummulitid fragments (N, encircled in white).

Fig. 9
Some examples of hm- to km- sized megablocks scattered in the Triora Olistostrome Member.
A) Panoramic view of Corte area, showing an extraformational megablock consisting of Upper Cretaceous marly limestones overlain, with an erosional surface (hatched white line), by m-thick beds of bioclastic rudstones of Nummulitic Limestone. The megablock is embedded within paraconglomerate deposits. The hatched black line indicates the thrust at the base of the San Remo – Monte Saccarello unit (SRS).
B) Panoramic view of an extraformational megablock characterized by a condensed succession ranging from Triassic dolostones to Eocene turbidites. The megablock is overlain by the thrust of the SRS unit (hatched black line), (Rocca Barbona sector).
C) Km-sized, exotic megablock at Colla Langan. In the foreground, the lowermost part of the block shows a chaotic structure, characterized by disharmonic folds and bed disruption.

Fig. 10
A) Mm- to cm-spaced cleavage developed in the pelite of Ventimiglia Flysch, that intersects the bedding at high angle. The spaced cleavage represents an axial plane foliation of flexural open folds that affect the Ventimiglia Flysch at a large scale, whose amplitude and wave length are in the order of tens of meters. Solid lines: bedding planes; hatched line: cleavage.

B) TOM paraconglomerates intensively sheared by low-angle contractional shear zones, that induce rotation and fragmentation of clasts and pressure dissolution in the pelite matrix.
C) Hm-sized Cretaceous megablock (Kmb) embedded in the upper part of TOM. In the right lower part of the figure foliated Eocene pelites (p) and paraconglomerates (P) are visible. Squared area refers to Fig. D. The dashed line indicates the spaced cleavage affecting the pelites.
D) Close up of Fig. C portraying the stratigraphic contact (white line) between the Cretaceous megablock (Kmb) and the Eocene pelites (p). The dashed line indicates the spaced cleavage affecting the pelites. Hammer for scale is 35 cm long.

Fig. 11
Sketch synthesizing the main steps in the diagenetic evolution of paraconglomerates. A first phase of veining (A) is followed by sliding that causes production of small fragments of veins (white angular grains) and paraconglomerate clasts partly bordered by veins (B). A second phase of veining takes place and is associated with calcite overgrowth around vein fragments (C). Finally, burial compaction produces breakage and crumpling of the second vein generation (D).

Fig. 12
Block diagram depicting the geotectonic setting in which TOM was formed. For further details see text. HF: *Helminthoides* Flysch; HFm: *Helminthoides* Flysch megablock; GM-NL: *Globigerina* Marls – Nummulitic Limestone; NLm: Nummulitic Limestone megablock; PDD: Provençal Dauphinois Domain; PDDm: Provençal Dauphinois Domain megablock; TOM: Triora Olistostrome member; VF: Ventimiglia Flysch. Orientation of the diagram is purely indicative and refers to present-day coordinates.

Fig. 13
Schematic sketch summarizing the main steps in the genesis of the TOM. Clasts of lithified carbonate units, exposed in fault-bounded, internally fractured, ridges, accumulate as breccias at the foot of the scarp and are covered by fine grained turbidites (A). Slope failures involve breccias and turbidite deposits including concretions and disrupted cemented beds giving rise to polygenic paraconglomerates (B). Catastrophic rock falls generate emplacement of megablocks (C) that may be further involved in gravitational movements together with breccias and paraconglomerates (D).

Fig. 14
Mm-spaced tectonic foliation (hatched black line) intersecting bedding at high angle (white line).

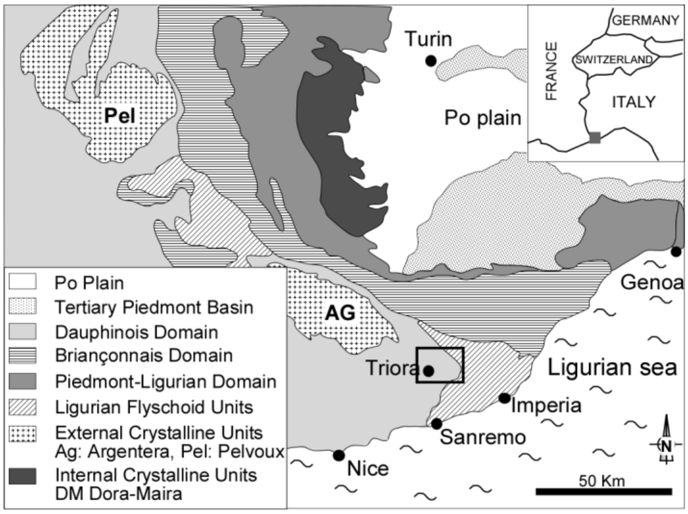
Turin
Po plain
GERMANY
FRANCE
SWITZERLAND
ITALY
Pel
AG
Genoa
Triora
Ligurian sea
Imperia
Sanremo
Nice
50 Km
N
Po Plain
Tertiary Piedmont Basin
Dauphinois Domain
Briançonnais Domain
Piedmont-Ligurian Domain
Ligurian Flyschoid Units
External Crystalline Units
Ag: Argentera, Pel: Pelvoux
Internal Crystalline Units
DM Dora-Maira

Fig.1

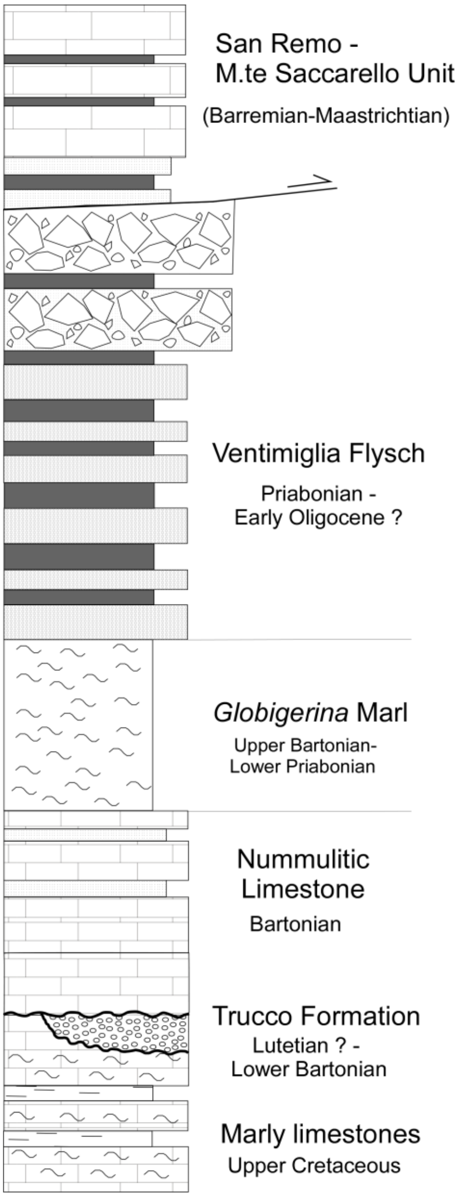
San Remo -
M.te Saccarello Unit
(Barremian-Maastrichtian)
Ventimiglia Flysch
Priabonian -
Early Oligocene ?
Globigerina Marl
Upper Bartonian-
Lower Priabonian
Nummulitic
Limestone
Bartonian
Trucco Formation
Lutetian ? -
Lower Bartonian
Marly limestones
Upper Cretaceous

Fig. 2

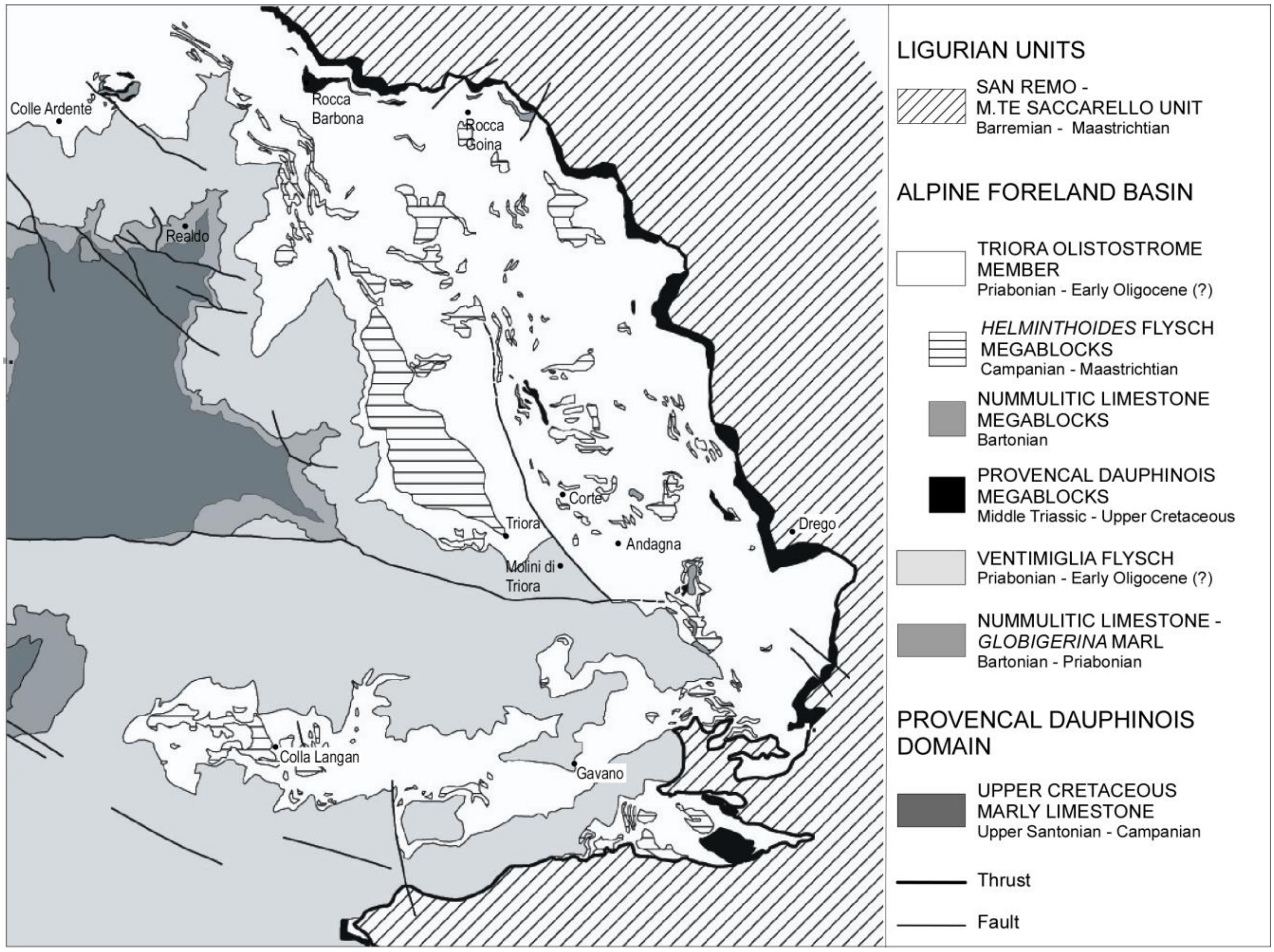
Colle Ardente
Rocca Barbona
Rocca Goina
Realdo
Corte
Triora
Andagna
Drego
Molini di Triora
Colla Langan
Gavano
LIGURIAN UNITS
SAN REMO - M.TE SACCARELLO UNIT
Barremian - Maastrichtian
ALPINE FORELAND BASIN
TRIORA OLISTOSTROME MEMBER
Priabonian - Early Oligocene (?)
HELMINTHOIDES FLYSCH MEGABLOCKS
Campanian - Maastrichtian
NUMMULITIC LIMESTONE MEGABLOCKS
Bartonian
PROVENCAL DAUPHINOIS MEGABLOCKS
Middle Triassic - Upper Cretaceous
VENTIMIGLIA FLYSCH
Priabonian - Early Oligocene (?)
NUMMULITIC LIMESTONE - GLOBIGERINA MARL
Bartonian - Priabonian
PROVENCAL DAUPHINOIS DOMAIN
UPPER CRETACEOUS MARLY LIMESTONE
Upper Santonian - Campanian
Thrust
Fault

Fig.3

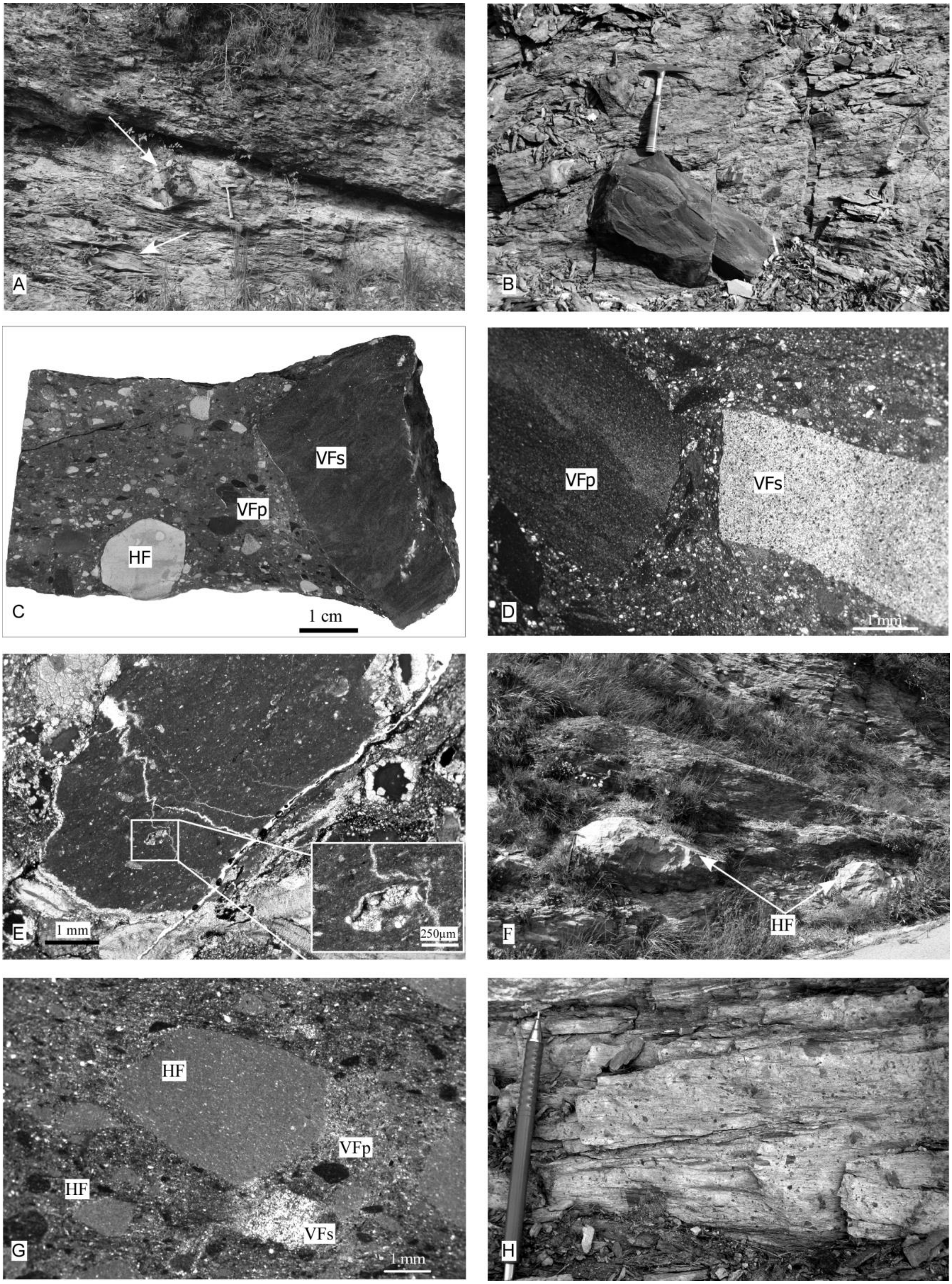
A
B
VFs
VFp
HF
C
1 cm
VFp
VFs
D
1 mm
E
1 mm
250µm
HF
F
HF
VFp
HF
VFs
G
1 mm
H

Fig. 4

Fig. 5

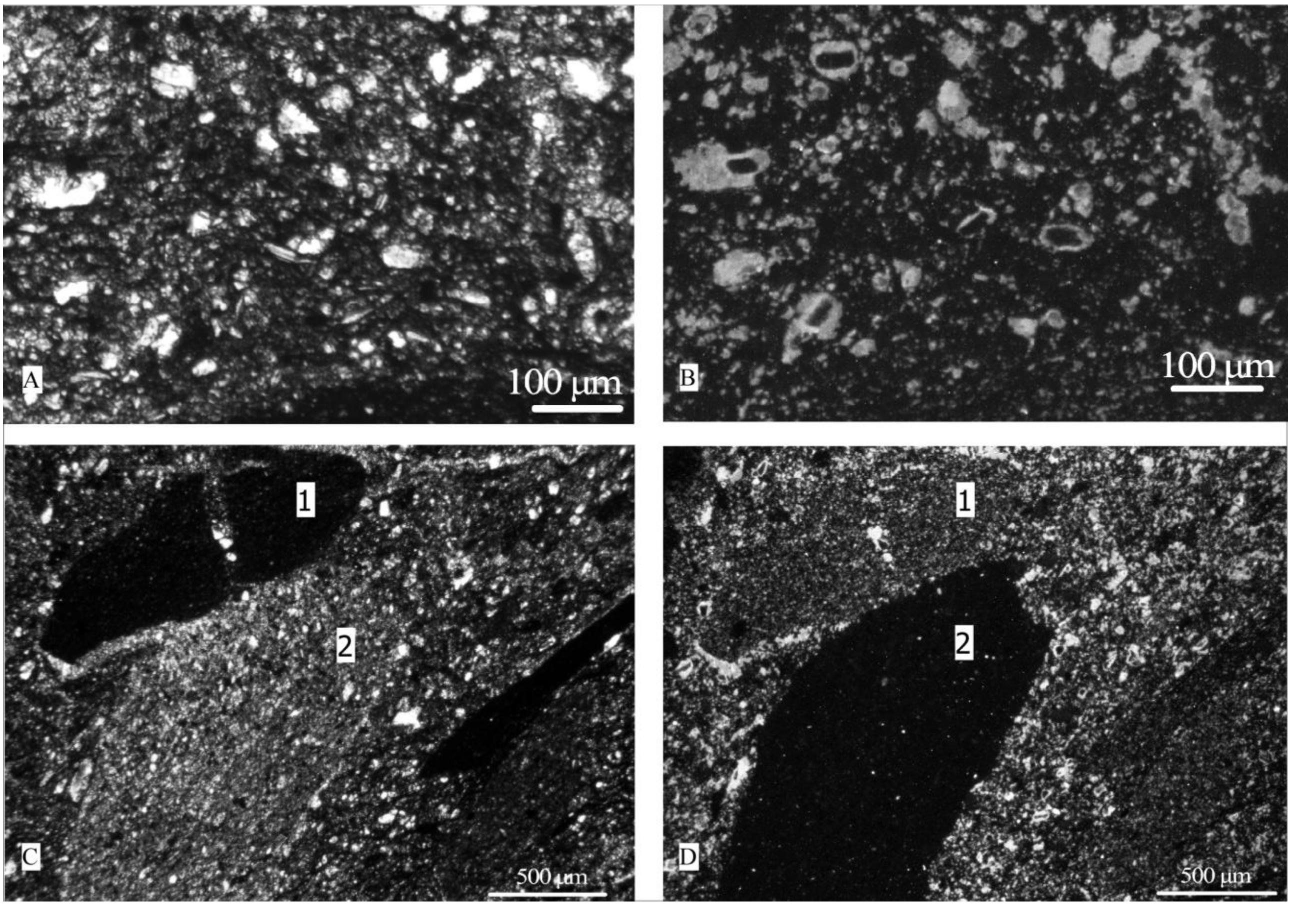

Fig. 6

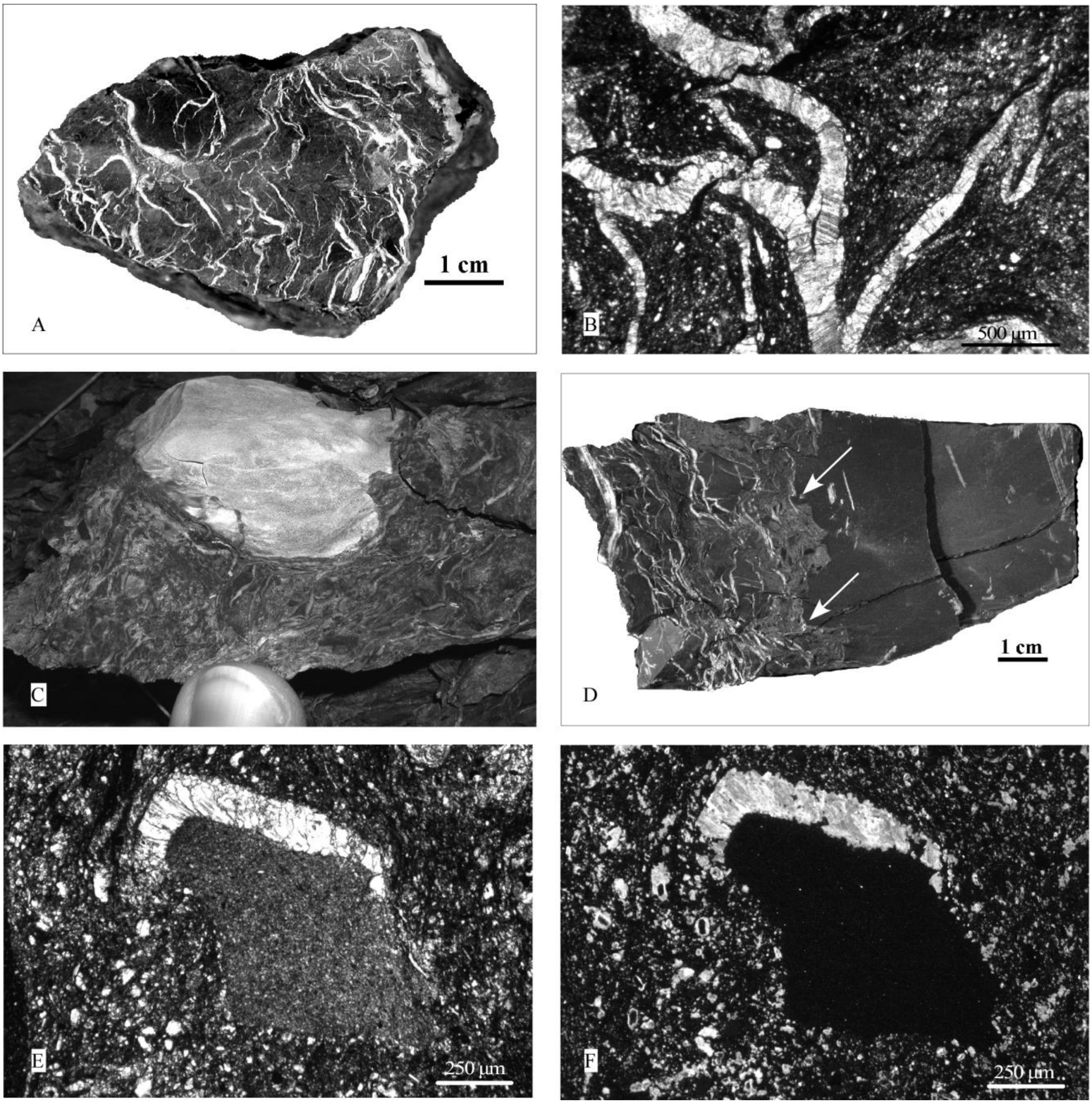

Fig. 7

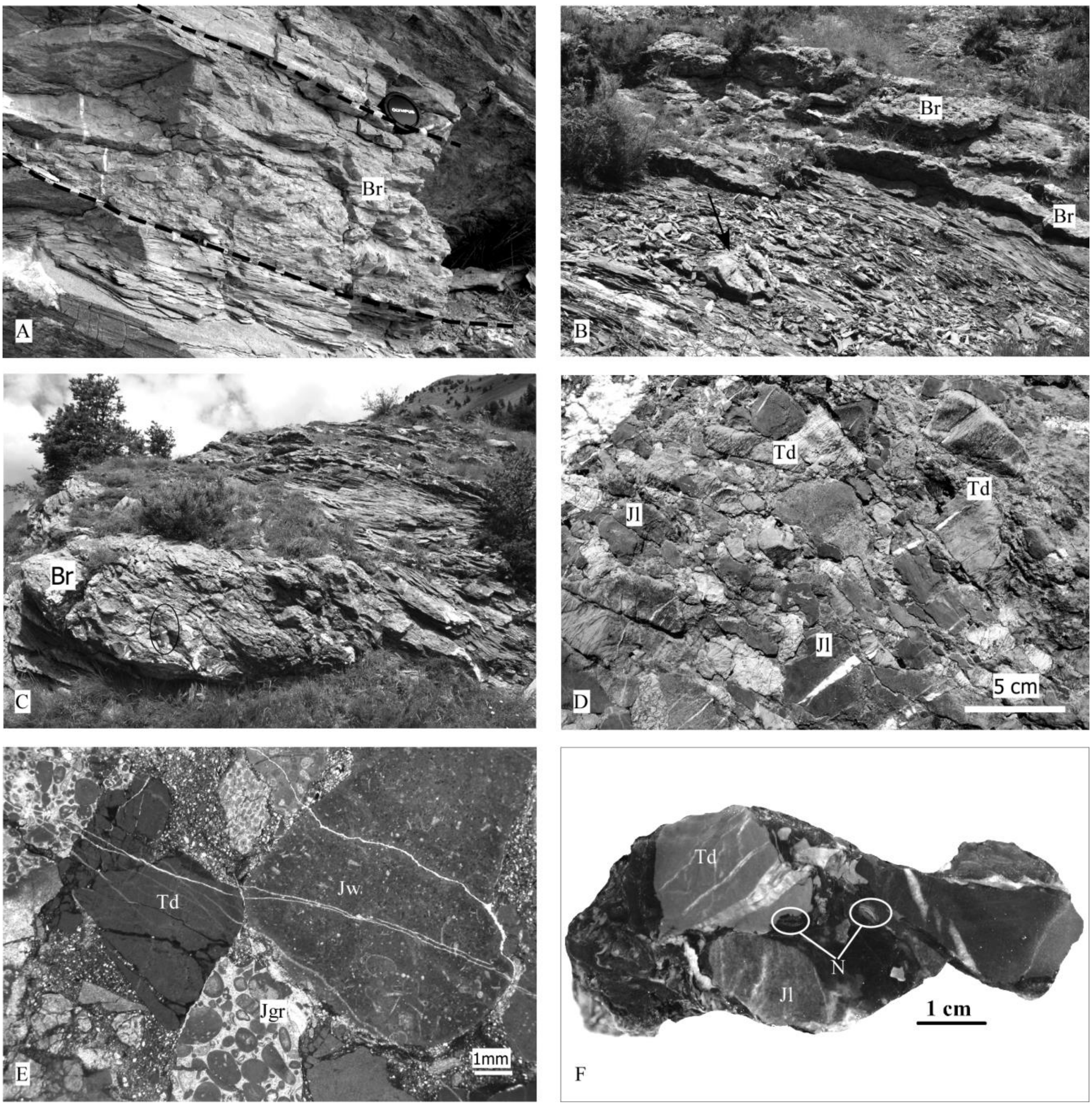

Fig. 8

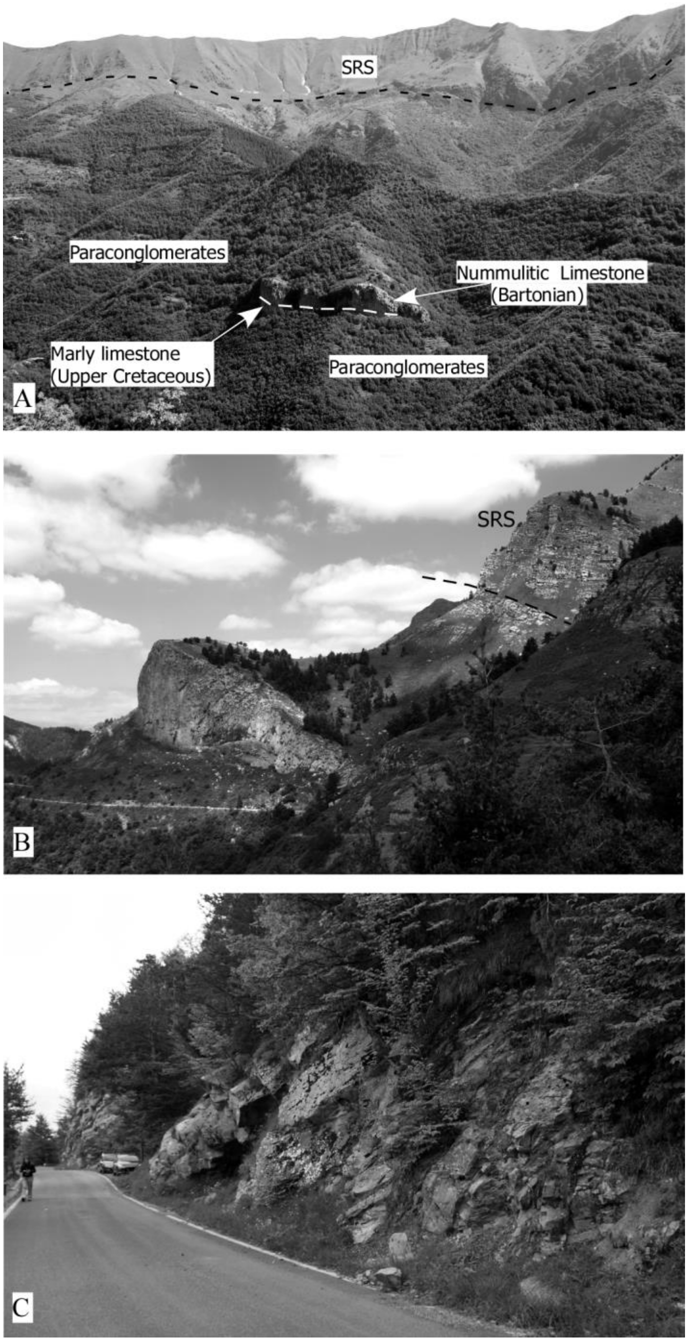
SRS
Paraconglomerates
Nummulitic Limestone
(Bartonian)
Marly limestone
(Upper Cretaceous)
Paraconglomerates
A
SRS
B
C

Fig. 9

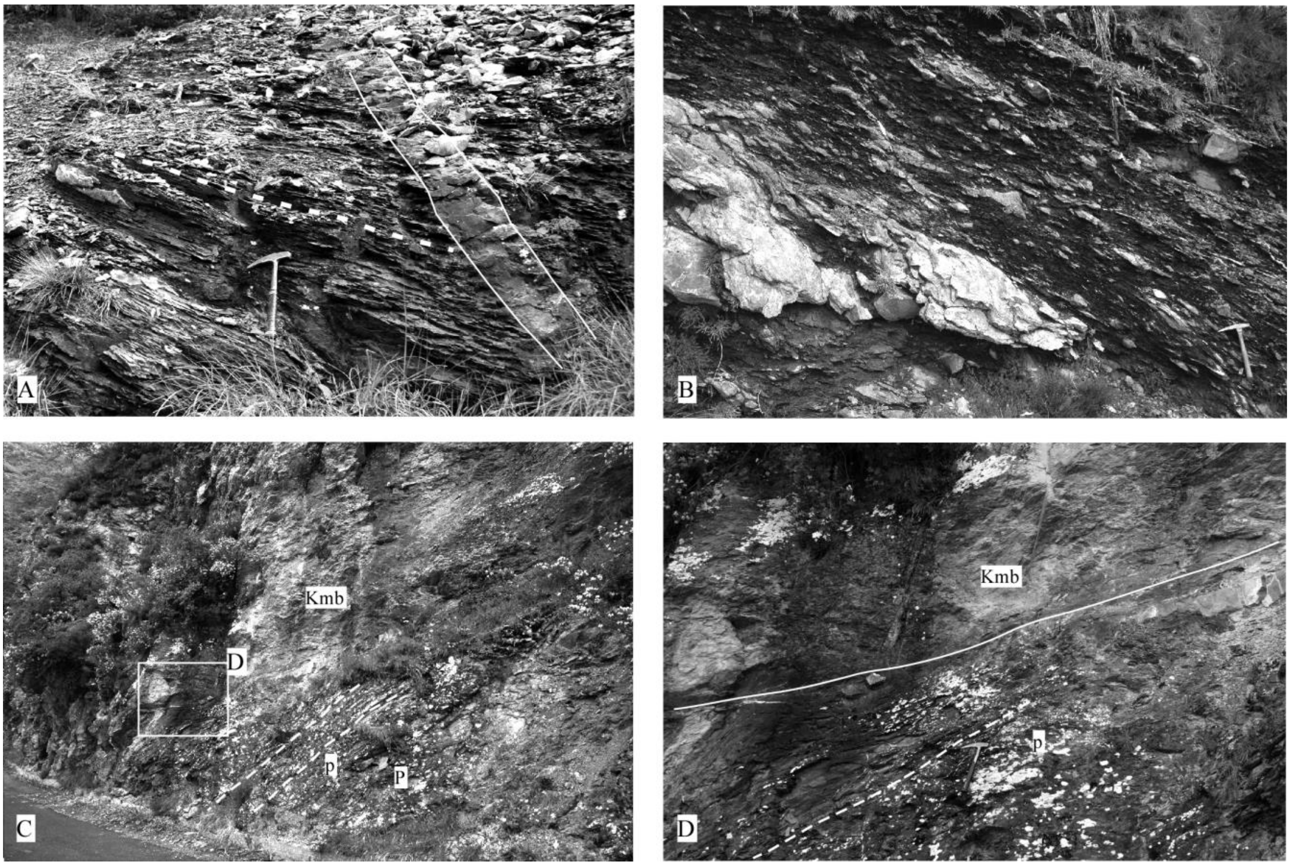

Fig. 10

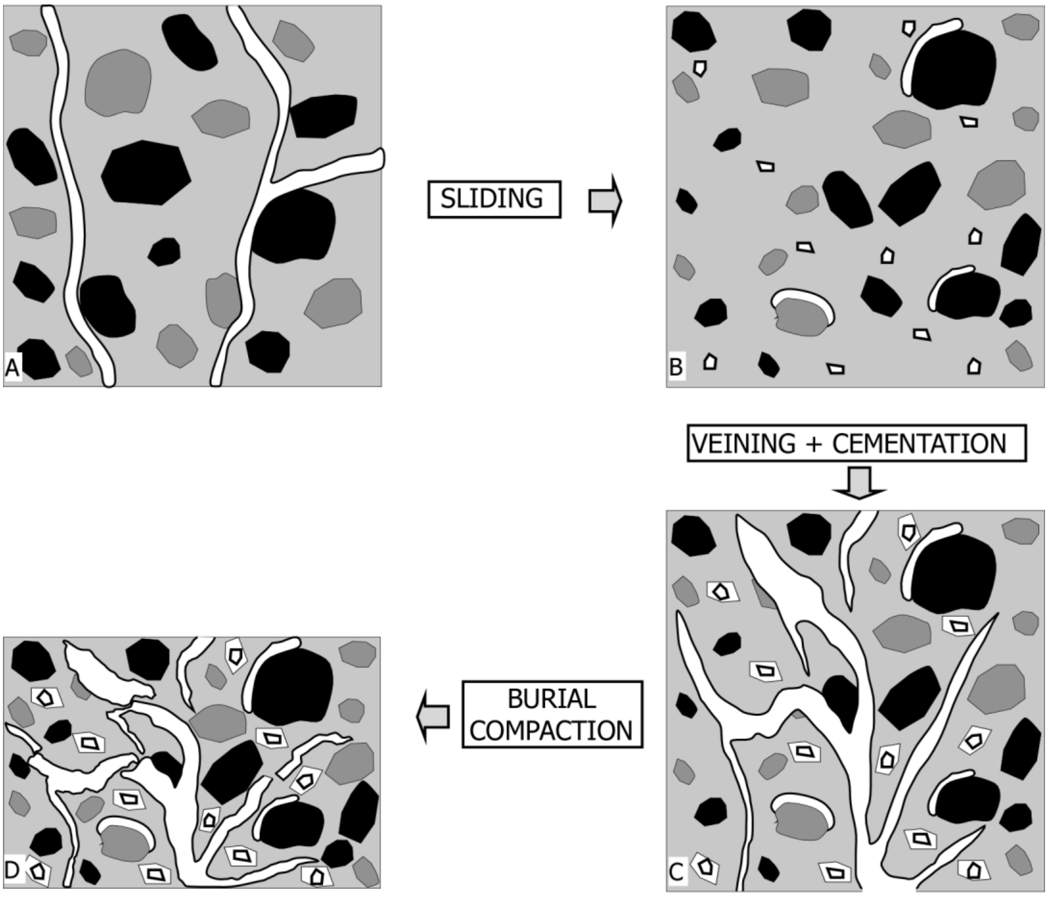
SLIDING
VEINING + CEMENTATION
BURIAL
COMPACTION
A
B
C
D

Fig. 11

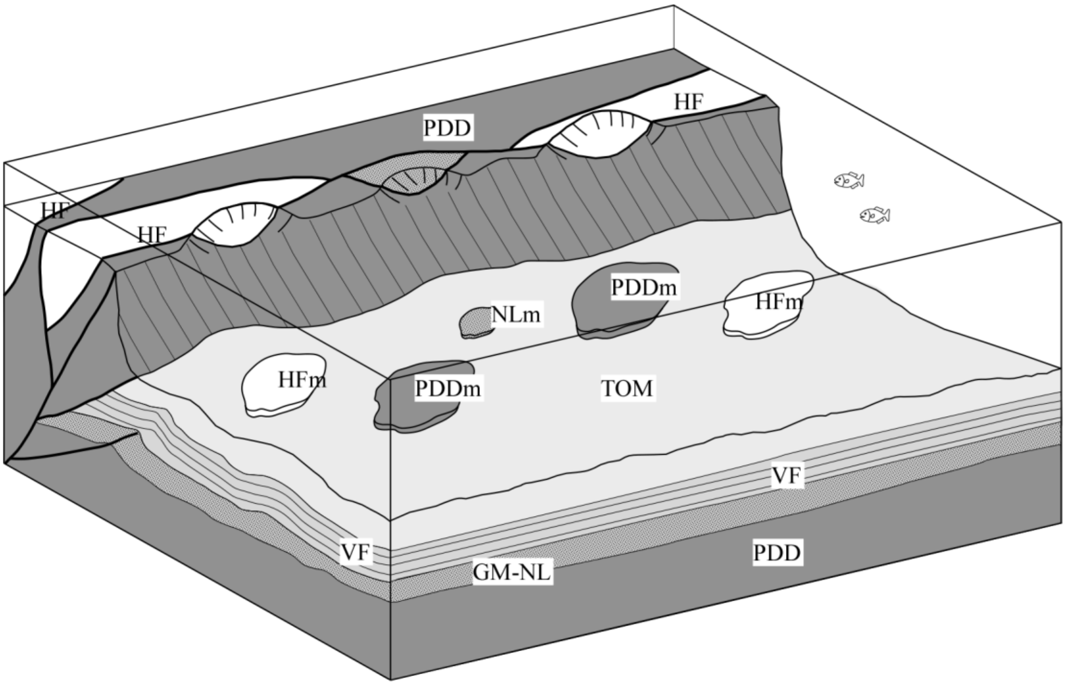
PDD
HF
HF
HF
PDDm
NLm
HFm
HFm
PDDm
TOM
VF
VF
GM-NL
PDD

Fig.12

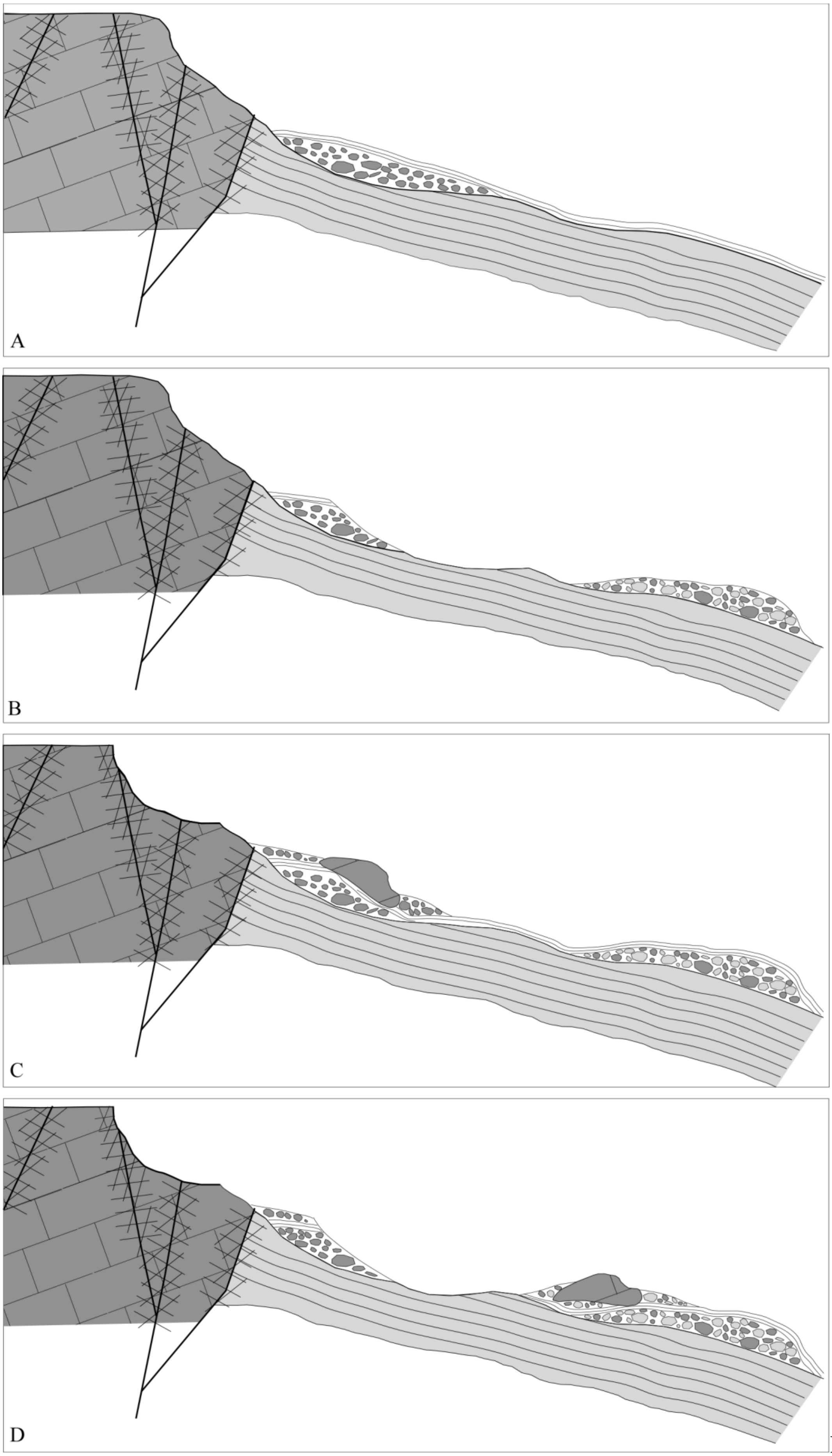

Fig-. 13

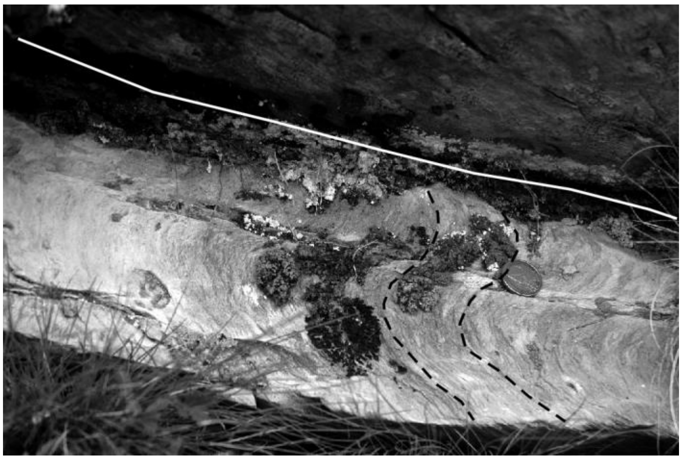

Fig. 14